A UNIQUE SOLUTION FOR PREVENTING CLOGGING OF FLOW CHANNELS BY GAS BUBBLES

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ABSTRACT

A novel solution is presented that deals with the well known problem of clogging in microfluidic channels caused by gas bubbles. The presented approach involves the use of a single channel with different, parallel cross sections. In each of these cross-sections different capillary forces act on the fluid and on potentially present bubbles. The latter are drawn into one of the cross sections, depending on their geometry and wetting behaviour, allowing a bypass, i.e. an ongoing, increased flow in the remaining available cross sections. The resulting drag on the bubble, caused by this flow, increases its mobility. In our experiments for low pressure differences the flow is increased by a factor of 4 and the mobility of the gas bubbles was increased by a factor of approximately 6 as compared to a conventional channel. This method greatly reduces the system susceptibility to clogging.

INTRODUCTION

It is a well-known phenomenon in microfluidics that small gas bubbles inside flow channels of small cross-section are able to completely block the liquid flow requiring high pressure gradients to move these bubbles [1]. Their emergence is known to strongly influence system behaviors [2], [3] in some cases completely blocking their functionality, in the worst case even causing their destruction.

The mentioned bubbles often occur simply by diffusion of gas through the tubing or by degassing of liquid due to shifts in temperature or pressure. Also vibrations can stimulate the formation of bubbles. Based on these effects the buildup of gas bubbles can hardly be prevented in microfluidic systems especially when these systems are operated over a longer period of time. This in turn requires adequate measures for the transportation or at least the tolerance of the bubbles.

CONCEPT

The presented concept applies a modified flow channel design which the authors refer to as *CHIC* (**Ch**annel **I**n **C**hannel) geometry. This design involves two parallel, connected channels as presented in figure 1.

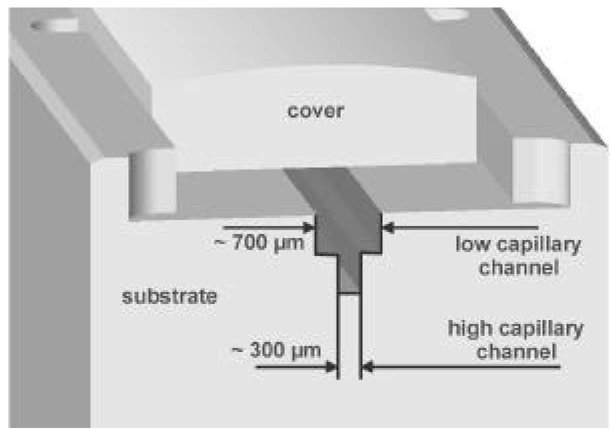

Fig. 1: Sketch of the *CHIC*-geometry (**CH**annel **I**n **C**hannel) which prevents clogging of channels by gas bubbles and increases movability of bubbles. In the experiments the transparent cover has been bonded by adhesives.

The capillary pressure p_{cap} for channels with rectangular cross sections depends on the height h and width b of the channel and on the effective surface tension σ_{eff} according to equation 1. Where σ_{eff} is derived from the wetting angle θ_c and the surface tension σ_l of the liquid.

$$p_{cap} = \sigma_{eff} \cdot \left(\frac{2}{b} + \frac{i}{h}\right) = \sigma_l \cdot \cos\Theta_C \cdot \left(\frac{2}{b} + \frac{i}{h}\right) \quad \text{equ. 1}$$

Equation 1 is valid for open (i=1) and also for closed capillary channels (i=2).

The two different resulting capillary pressures p_{cap} for the different channel geometries of the large and small channel are taken advantage of by using the different channel cross sections in parallel.

This has two important consequences:

Depending on the involved fluids, i.e. liquid and gas combination, and the resulting inter-fluid surface tensions, a bubble initially covering the complete cross section of the *CHIC*-type geometry is drawn into one of the channel cross sections. In general, in hydrophilic channels the gas bubble moves into that part of the channel with the larger cross section.

The remaining part of the channel in turn takes in the remaining liquid acting as bypass. This ensures a continued liquid flow at an increased flow velocity in the open section. That is under the assumption that the bubble blocks the other section, reducing the active cross section. The functionality of this principle has been proven for a channel geometry of 700 x 500 µm for the larger and 300 x 100 µm for the smaller channel. Bubbles were formed by degassing of liquid or by inserting them with a syringe.

In consequence of the above mentioned effect, the increased flow velocity of the fluid inside the bypass causes a pressure shift along the position of the bypass, i.e. across the position of the bubble. Additionally the relative motion between the gas bubble and the liquid exercises shear forces at their joint. Both effects in turn increase the bubble mobility and prevent clogging.

Therefore the *CHIC*-concept has two advantages: first it leads to a bypass and therefore prevents clogging of the flow channel. Second it increases the mobility of bubbles in microchannels.

MEASUREMENTS

The *CHIC*-concept was tested using cross sections of 700 x 500 µm for the larger and 300 x 100 µm for the smaller channel (figure 1). The channels are 150 mm long. They were manufactured of plastics (ABS) by injection molding and closed using a transparent plastic cover. As liquid water colored with a blue dye was used for optimal visualization. The wetting angle Θ_c between fluid and the plastics material and the surface tension σ_l of the liquid were determined to 78° and 70 mN/m respectively.
The capillary pressures inside the two cross sections were calculated at 100 Pa and 243 Pa respectively.

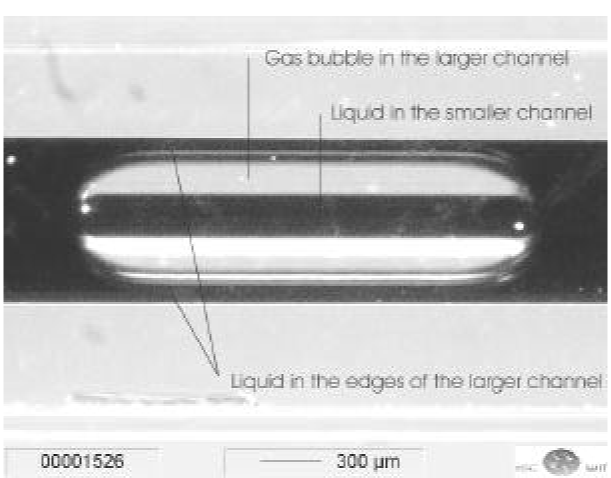

Fig. 2: Photograph of a bubble in the *CHIC*-desing. It can be seen that the smaller channel is filled with liquid and acts as a liquid bypass.

For the system analysis gas bubbles of different sizes were injected into the system using a syringe. As demonstrated in figure 2 all the injected bubbles settled exclusively in the larger cross section while the smaller channel beneath was filled with the liquid. This demonstrated the effectiveness of the bypass as well as the functionality of the concept.

For evaluating the prevention of clogging and the improved flow behavior of the *CHIC*-concept the flow channels were used in a horizontal position as indicated in figure 3. After filling the channel with liquid, defined bubbles of 10 mm length were injected using a syringe. Then the flow rate of the liquid was determined in dependence on the pressure difference over the channel structure.

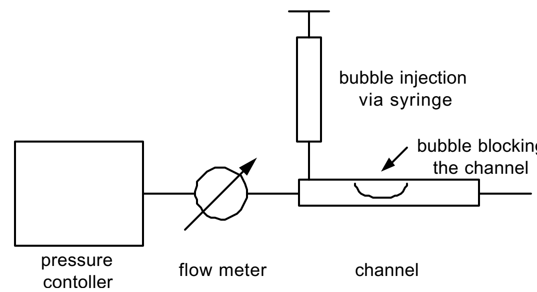

Fig. 3: experimental setup for the measurement of the flow rate in the capillary channels in dependence on the prerssure difference

The dependence of the flow rate on the pressure differences is shown in figure 4. As can be seen, the *CHIC*-type geometry improves the flow rates for low pressure differences by a factor of 4.

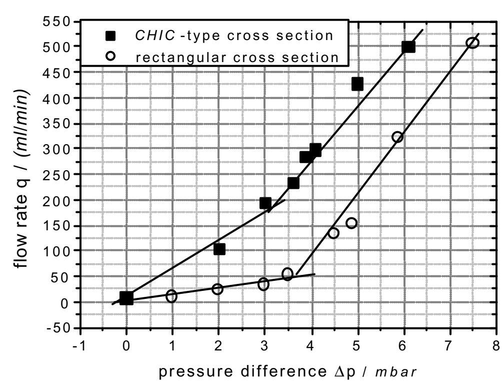

Fig. 4: measured flow rate q in dependence on the pressure difference for a CHIC-type channel and a conventional channel. In both channels a bubble of 10 mm length is inserted. The different cross section areas are taken into account by normalizing them.

In a channel of circular cross-section, gas bubbles are shifted by the meniscus of the liquid and therefore move with the same velocity as the liquid. High pressure differences are needed to push the bubble through the channel. That means that for low pressure differences there will be no flow rate.

In the conventional channel with rectangular cross-section one can separate two cases. In the low pressure case the flow rate results from liquid passing the bubble in the edges of the channel (see figure 2 for liquid in the edges of the larger channel). This presents a “natural *CHIC*-effect”. In this case the bubble does not move and it represents a rather high fluidic resistor. As can be seen from figure 4 there is only a low increase of flow rate with pressure in the first case.

In our experiments, for pressures higher than 3,5 mbar a increase of the slope of the flow rate dependence on pressure can be observed. That means that for higher pressures the fluidic resistance of the bubble decreases. This is due to the bubble being pushed by the liquid through the channel. The bubble now is no longer immobile.

For higher pressures the *CHIC*-channel acts as the conventional rectangular cross-sectioned channel. The bubbles are pushed by the fluid through the channel.

For low pressure conditions, that means when the pressure is not high enough to move the bubble, the bypass resulting from the geometry of the *CHIC*-channel leads to a smaller decrease of the flow rate due to a smaller ratio of the total cross section being blocked by the bubble. Therefore bubbles in *CHIC*-type channels lead to a smaller increase of the fluidic resistance than in conventional channels.

In order to quantify the bubble mobility inside the channel the flow channels were brought into an upright position as indicated in figure 5.

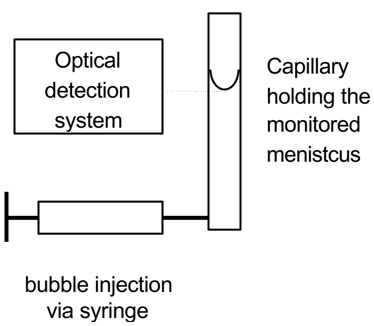

Fig. 5: experimental setup for the measurement of the bubble velocity

Following the injection of defined bubbles at the lower opening of the channel the motion of the bubble was then optically monitored. Based on the involved forces the bubbles rose to the upper end of the vertical channel at a defined velocity as indicated in figure 6.

Using a standard, single cross sectional channel in an identical experiment a comparison of the different channels was achieved. The results are shown in figure 6 clearly indicating an increased flow velocity by a factor of approximately 6 inside the *CHIC*-type channel as compared to the original channel geometry with an identical overall cross sectional area.

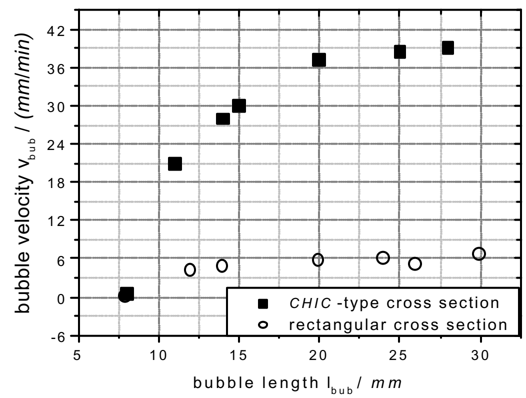

Fig. 6: measured gas bubble mobility in dependence on bubble size. The mobility in the *CHIC*-type channel is nearly one order of magnitude higher compared to the standard rectangular flow channel.

The situation leading to the rise of the bubbles can be explained using figure 7. There is no flow into or out of the channel. That means that there has to be a balance between gas volume moving upwards and liquid volume moving downwards.

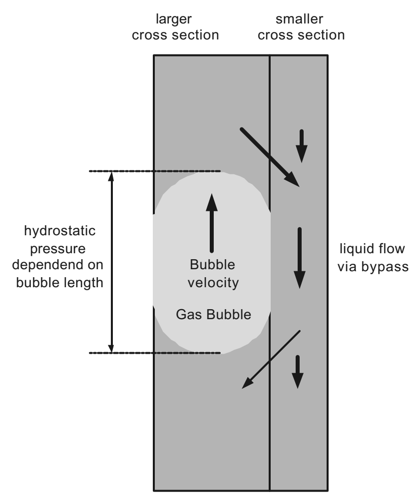

Fig. 7: Situation for a bubble in an upright CHIC-channel. The bubble moves due to lifting forces

The gas volume rate Φ_{gas} can be calculated from the measured bubbles velocity and the cross section of the larger channel $h_{LC} \cdot b_{LC}$ according to eqn. 2:

$$\Phi_{gas} = v_{bub} \cdot h_{LC} \cdot b_{LC} \qquad \text{eqn. 2}$$

The liquid volume rate Φ_{liq} can be determined from the pressure difference p_{hyd} and from the fluidic resistance of the smaller channel R_{SC}:

$$\Phi_{liq} = \frac{p_{hyd}}{R_{SC}} \qquad \text{eqn. 3}$$

Where the pressure difference p_{hyd} between upper and lower meniscus of the bubble and the fluidic resistance of the smaller channel R_{SC} according to [4] are respectively:

$$p_{hyd} = \rho_{liq} \cdot g \cdot l_{bub} \qquad \text{eqn. 4}$$

$$R_{sc} = \zeta \cdot \frac{8 \cdot \eta \cdot l_{bub} \cdot (h_{sc} + b_{sc})^2}{h_{sc}^3 \cdot b_{sc}^3} \qquad \text{eqn. 5}$$

From the flow rates balance the bubble velocity can be derived according to eqn. 6:

$$v_{bub} = \frac{p_{hyd}}{R_{SC} \cdot h_{LC} \cdot b_{LC}} = \frac{\rho \cdot g \cdot h_{SC}^3 \cdot b_{SC}^3}{8 \cdot \eta \cdot \zeta \cdot (h_{SC} + b_{SC})^2 \cdot h_{LC} \cdot b_{LC}} \qquad \text{eqn. 6}$$

For the parameters given in the experimental setup the bubble velocity is calculated to 42 mm/min showing an excellent agreement to the measurements.
For small bubbles there are additional effects such as wall friction that lead to a decreased bubble velocity.

The experiments showed that the bubble velocity was increased in the *CHIC*-type channel. In the conventional channel only the “natural *CHIC*-effect” in the edges of the channel are available for fluid flow. They have a much higher fluidic resistance resulting in lower bubble velocities.

CONCLUSIONS

An unique solution to an old and well-known problem in microfluidics is presented: the clogging of flow channels caused by immobile gas bubbles.
Reduced clogging and enhanced bubble mobility were demonstrated using the *CHIC*-type approach with geometries typical for microfluidic applications.
In consequence to the experiments the setup was introduced into the design of an electronic fountain pen at HSG-IMIT [5] where it has proven to operate as desired, reducing the susceptibility to clogging when the system operated with real world fluids. Due to the application of the *CHIC*-concept the microdosage system fulfills the requirements independent on the presence of bubbles in the channels. Additionally bubbles in the system are moved using lifting forces. In this setup not a single case of clogging caused by bubble formation was witnessed.
Future work on this topic will include the application of the simple, yet highly effective *CHIC*-concept for a number of microfluidic devices such as bubble traps.

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